A Review of Thermoelectric Multicouple Technologies for Space Power Systems

XVI Interstate Conference «Thermoelectrics and their Applications»

Saint-Petersburg, Russia

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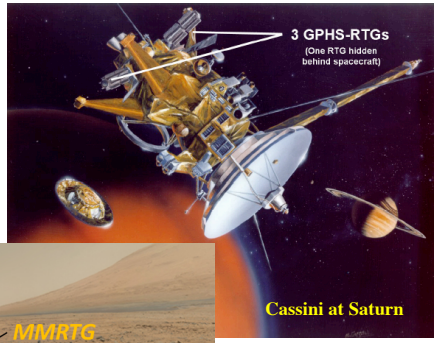
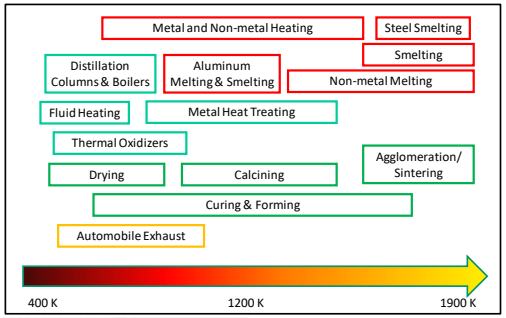
Outline

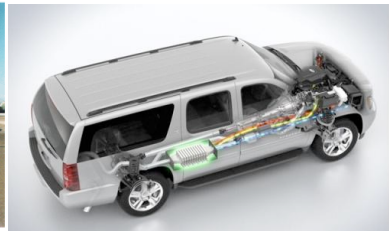
- Background
- RTGs for Space Mission – Record of extraordinary accomplishments
- Key thermoelectric converter design features in heritage systems and drivers for more capable power systems
- Overview of historical multicouple technologies for advanced system concepts
- Next Generation RTG concept: system modularity as key attribute
- Summary

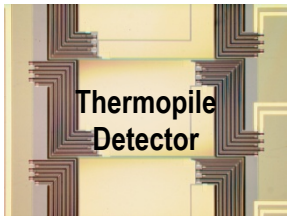
Breadth of Thermoelectric (TE) Applications
Power, Cooling, Sensing

Ultra-Reliable
(30+ Years)





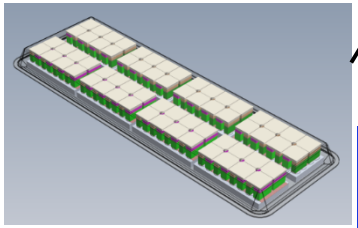




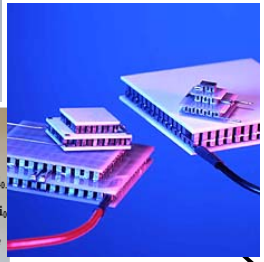
IR Sensing

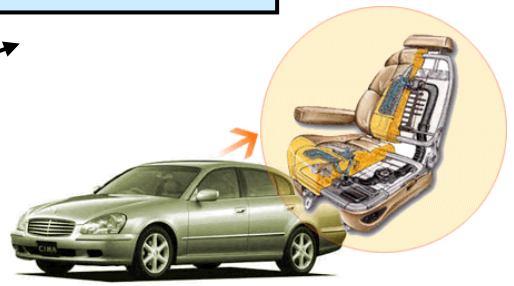
Waste Heat Recovery & Energy Harvesting

60 years of NASA Investment in High Temperature TE Power Generation Technology for Deep Space Science Exploration



Small scale Refrigeration





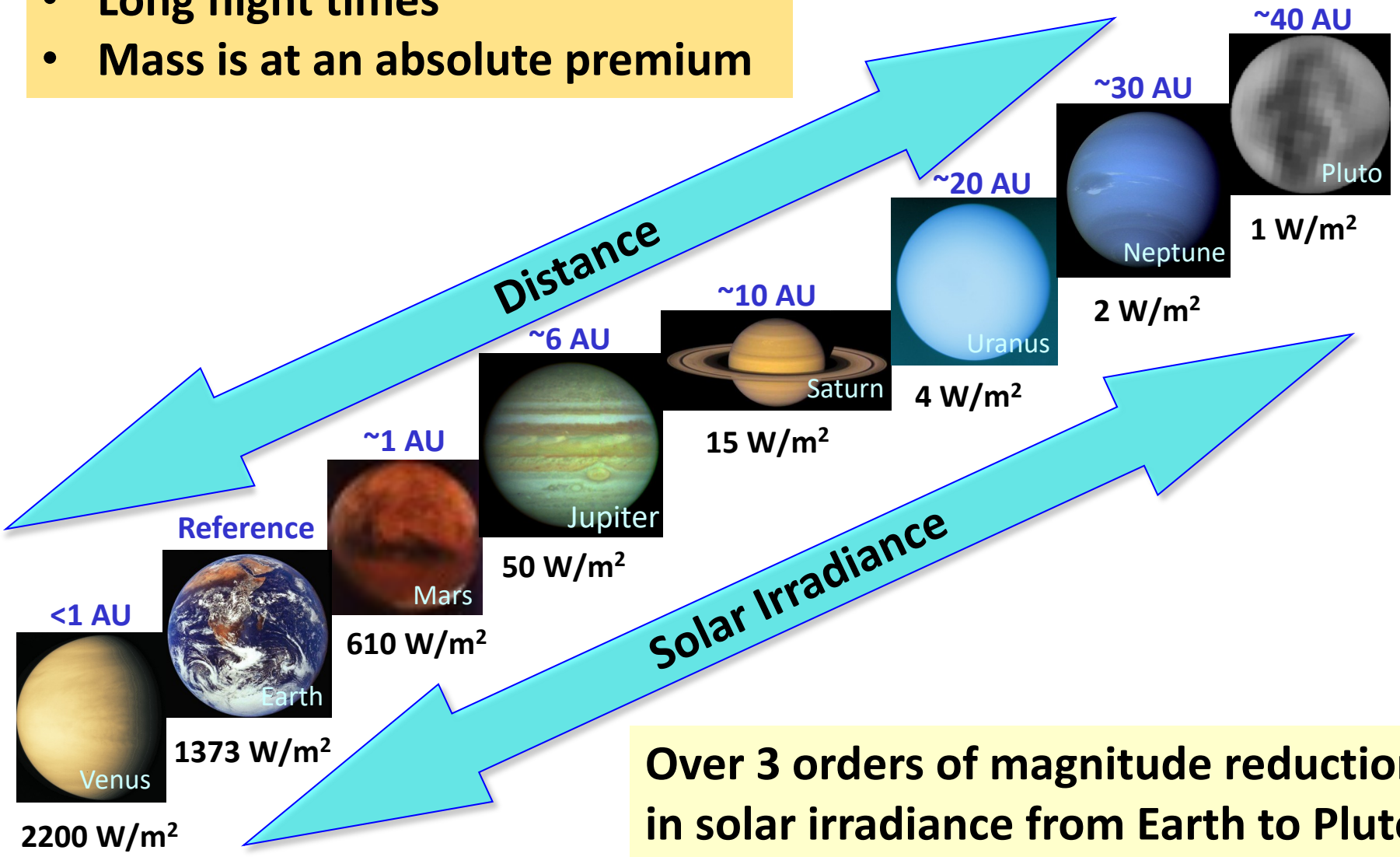
Autonomous Remote Power Generator

TE Converter building blocks: Couples and multi-couple Modules

Active heated & cooled seating system

Major Power Challenges of Solar System Missions

- Long flight times
- Mass is at an absolute premium



Over 3 orders of magnitude reduction in solar irradiance from Earth to Pluto

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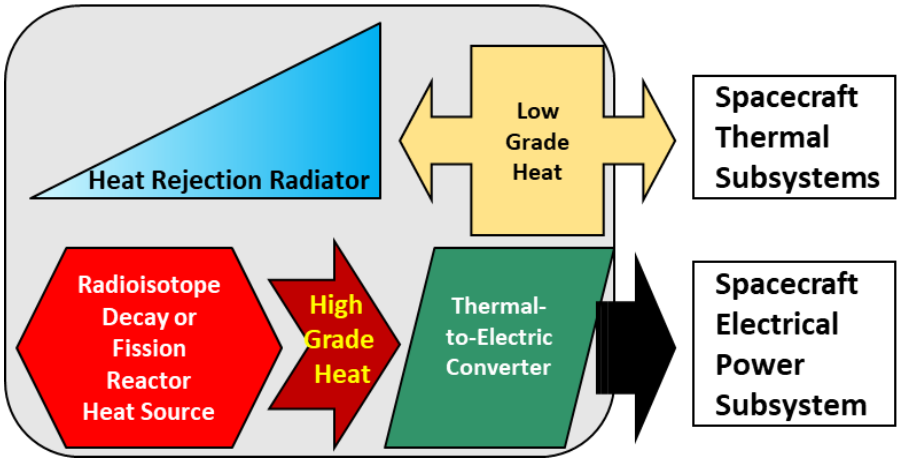
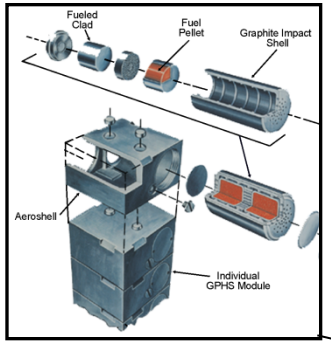
RTG Technology - What is an RTG?

Space Nuclear Power System Functional Diagram

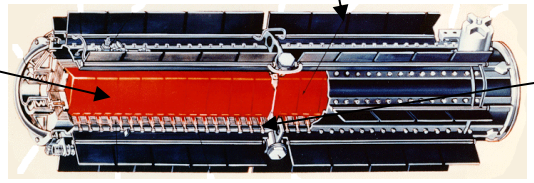


Absolute Reliability, Specific Power and Fuel Usage are the Drivers!

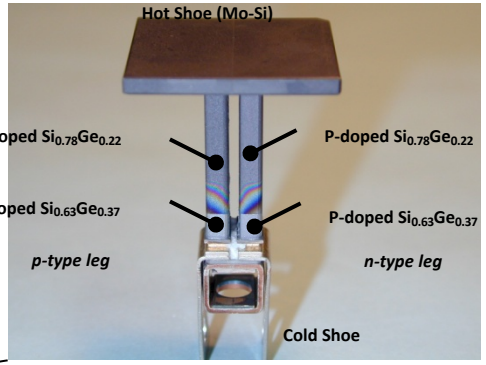


Heat Source Assembly
(GPHS Modules)

Housing & Radiator Assembly



GPHS-Radioisotope Thermoelectric Generator (RTG)



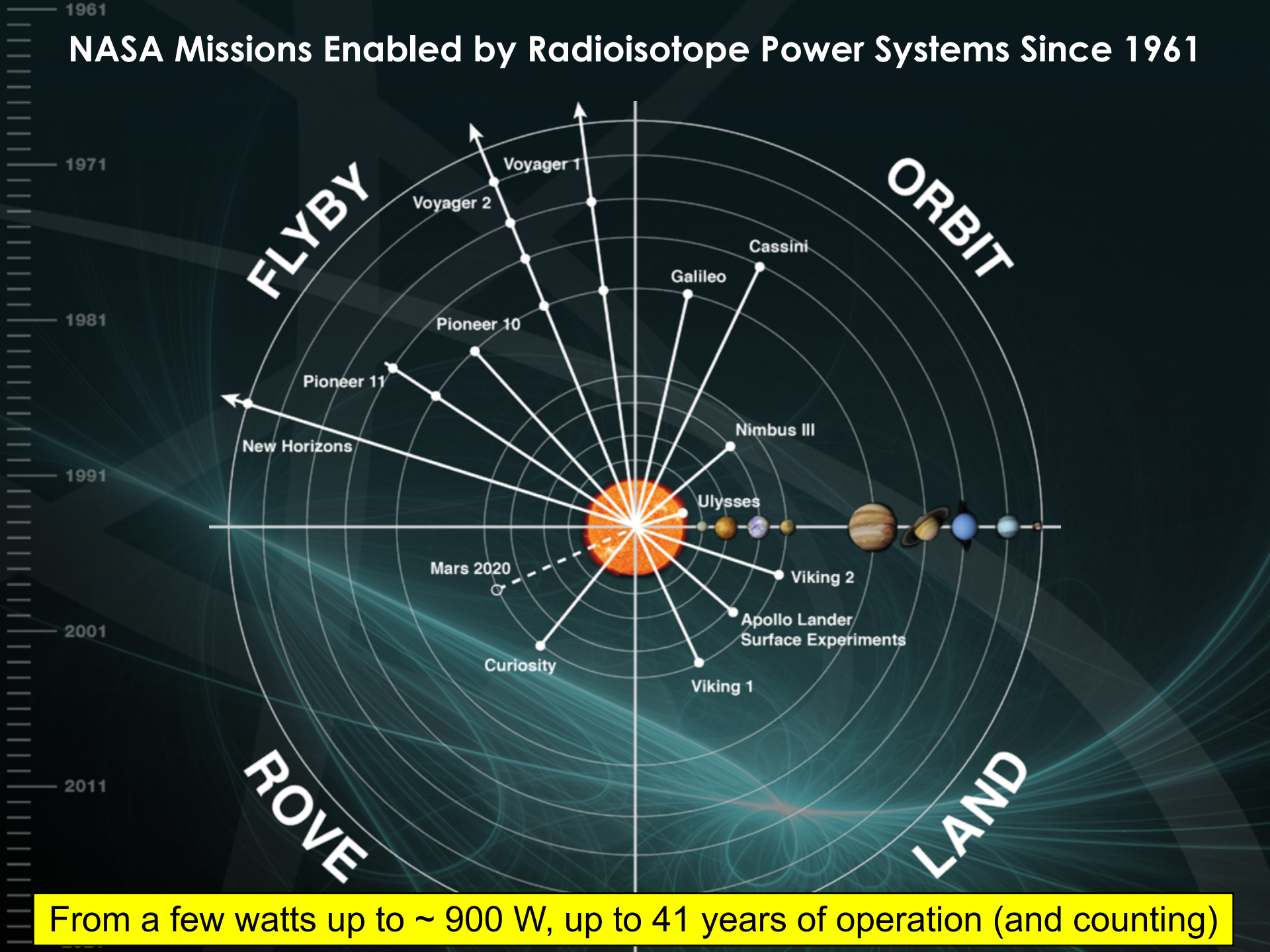
Converter = Array of TE Devices

Conversion Efficiency

Carnot: $\frac{T_{hot}-T_{cold}}{T_{hot}}$ TE Materials: $\frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+\frac{T_{cold}}{T_{hot}}}$

$$\eta_{\max}=\frac{T_{hot}-T_{cold}}{T_{hot}}\cdot\frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+\frac{T_{cold}}{T_{hot}}}$$

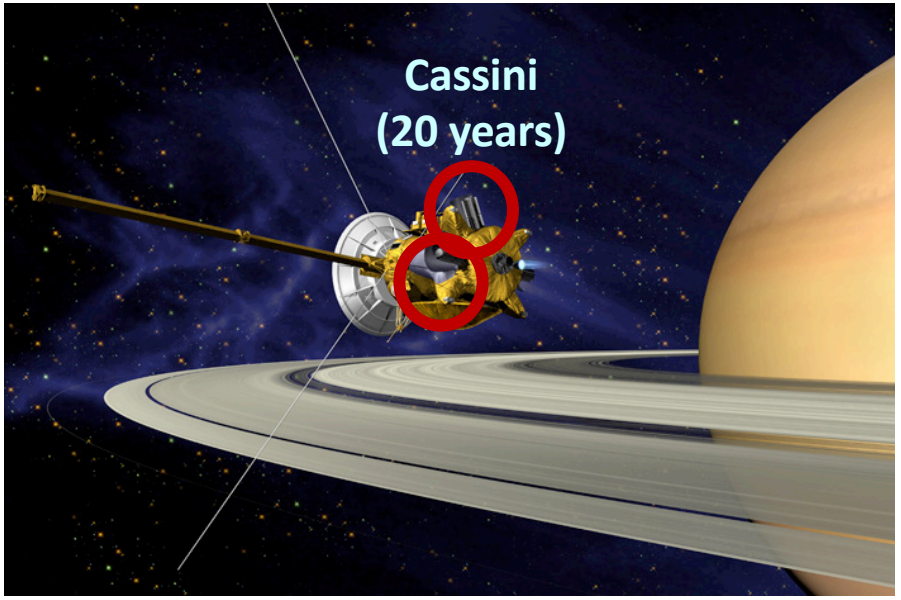
NASA Missions Enabled by Radioisotope Power Systems Since 1961



From a few watts up to ~ 900 W, up to 41 years of operation (and counting)

Thermoelectrics in Space: A 50^{+}-year Success Story

Based on "Old" TE Materials & Devices: PbTe, TAGS (1960's) and Si-Ge (1970's)



The Success Story to Date

- For over 50 years, space nuclear power sources based on thermoelectric energy conversion have proved to be safe, reliable, sturdy, long-lived sources of electrical power.
- Since 1961, the U.S. has successfully launched 43 nuclear power sources (42 radioisotope thermoelectric generators and one nuclear reactor) on 27 space missions along with hundreds of radioisotope heater units (RHUs).
- The SNAP-10A space nuclear reactor power system demonstrated the viability of automatically controlled, liquid-metal-cooled reactors for space applications.
- RTGS have enabled some of the most challenging and scientifically exciting missions in human history
- In general, RTGs have exceeded their mission requirements by providing power at or above that required and beyond the planned mission lifetime.

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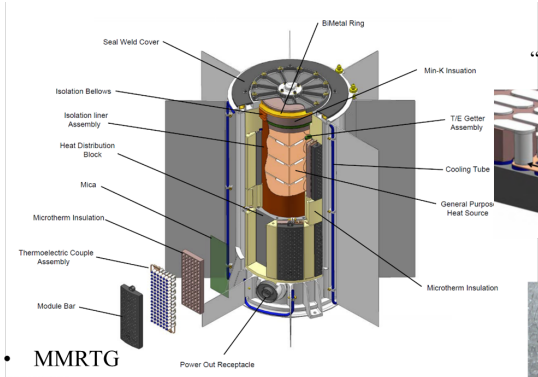
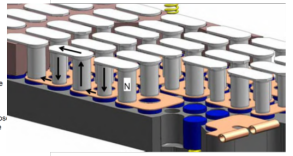
Two Basic RTG Configurations

Converter consists of Discrete Array(s) of Single p-n Couples

- Conductive coupling to heat source
  - Heat transfer from heat source achieved through an intermediate heat distribution block (HDB)
  - HDB conductively or radiatively coupled to packaged radioisotope heat source
  - "skeleton" TE couples are bonded into "modules" on their cold side electrodes
  - Spring-loading force from the cold side pushing couples onto the HDB
  - Cold side is conductively coupled to the radiator



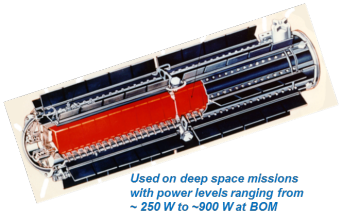
"48-couple Module"



"Couple"

- MMRTG
  - Developed to "Multi-Mission" specifications
  - 768 Spring-loaded couples, arrayed into 16 modules
  - n-type PbTe and p-type TAGS/(Pb,Sn)Te
  - Heat source: ~ 2000 Wth (8 GPHS)
  - BOL: Power: ~ 122 W_e; Specific power: ~ 2.8 W/kg

Spring-Loaded PbTe/TAGS Couple Technology

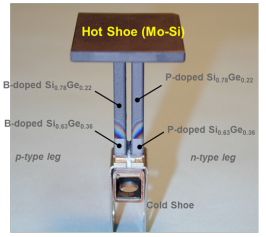


Used on deep space missions with power levels ranging from ~ 250 W to ~900 W at BOM

- Vacuum-only operation
- Heat source: ~ 4500 W_{th} (18 GPHS)
- Power: ~ 295 W_e
- Specific power: ~ 5.1 W/kg
- System efficiency ~ 6.5%

- Radiative coupling to heat source
  - Radiative heat transfer from heat source onto a heat collector that is part of the TE couple
  - Single TE couples are cantilevered structures directly bolted onto the radiator ("cold shoe")
  - Cold shoe is conductively coupled to the radiator (mechanical and thermal interface)

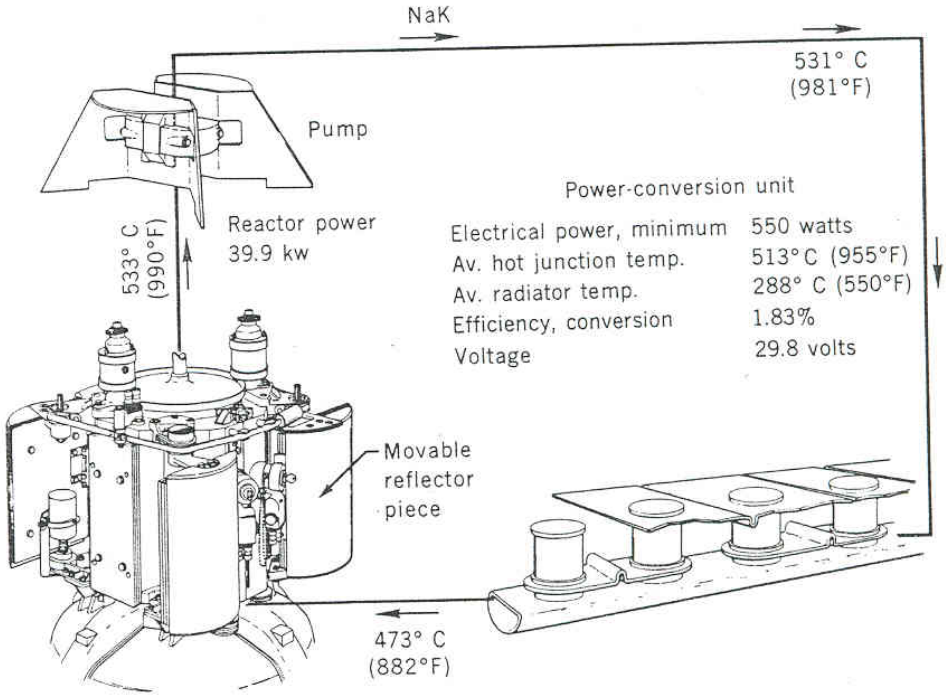
- Array of discrete Si-Ge TE couples
  - 572 total
  - Series-parallel laddering circuit
- Cantilevered configuration with radiative coupling to heat source
- Segmented Legs
  - Higher Ge content on lower segment
- $T_{hot\ junction}$ ~ 1273 K
- $T_{cold\ junction}$ ~ 573 K
- 7.5% efficient



Cantilevered Si-Ge Couple Technology

SNAP 10A Space Power Reactor

- Completed ; in orbit April 1965
- Energy conversion : Thermoelectric (SiGe materials)
- Array of SiGe couples mounted between the hot NaK pipes and the radiator
- Reactor thermal power : 39.9 kW
- System power level and mass: ~500W and 427 kg
- Hot/cold junction temperatures : 786K / 561K
- System (Converter) efficiency : 1.6% (1.83%)
- Voltage : 29.8 V



Drivers for More Capable Power Systems

- Historically only "one RTG size" available at any point in time
  - Limited or no modularity
- Wider range of nuclear power system levels is needed to better serve future mission needs
  - From ≤ 40 W up to ~ 500 W for vast majority of robotic science and exploration mission concepts
  - Some kW-class robotic science missions and higher power for human precursor mission concepts
  - 10-100 kW class human outpost mission concepts
- Heritage TE converter designs based on arrays of discrete couples are ill suited
  - At low power levels, couple sizing to maintain high output voltage requirements becomes impractical
  - At high power levels, converter assembly and system integration become impractical
- Need to develop common converter technology building blocks that can adapt to future system concepts

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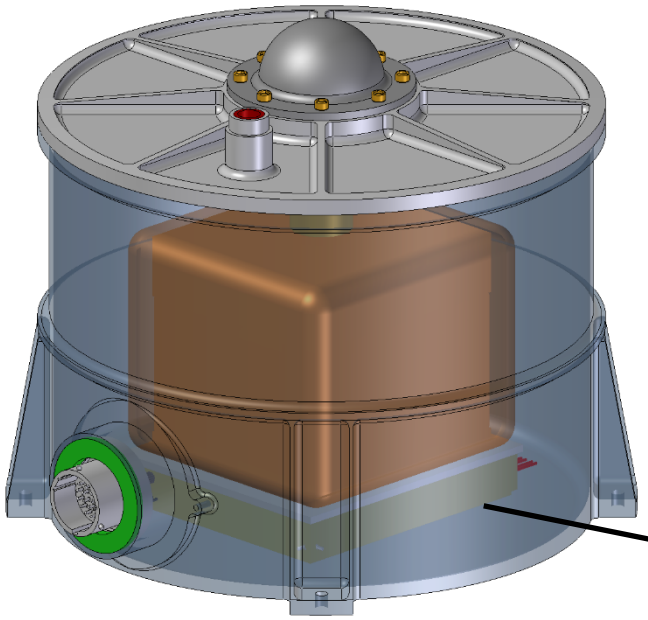
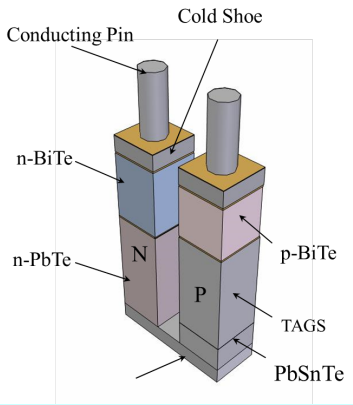
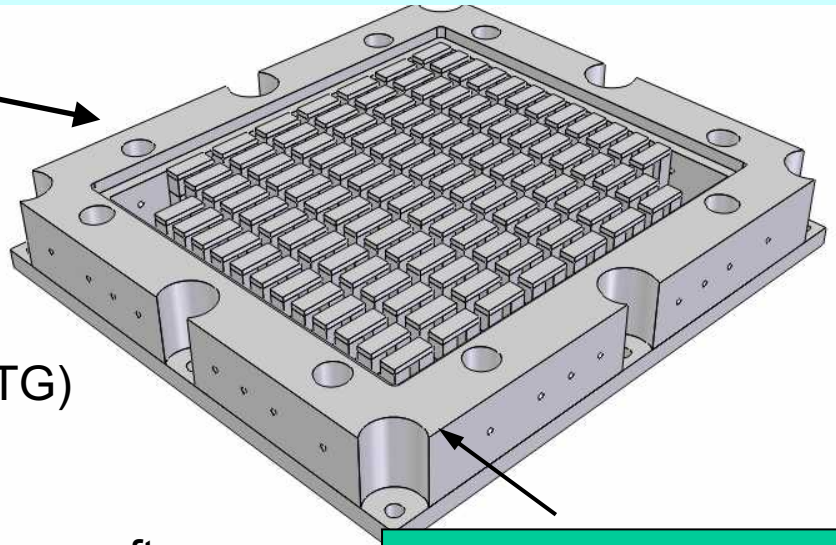
"Small RTG" Concept: "Close-packed" Thermoelectric Multicouple



- N leg: BiTe/PbTe
- P leg: BiTe/TAGS/PbSnTe
  - T_{hj} = 800 K
  - T_{cj} = 400 K
- TE couples are mounted on a printed wiring board which puts them electrically in series and/or parallel connection



Compressively-loaded Thermoelectric "Multicouple": array of discrete couples, similar to heritage RTG technology

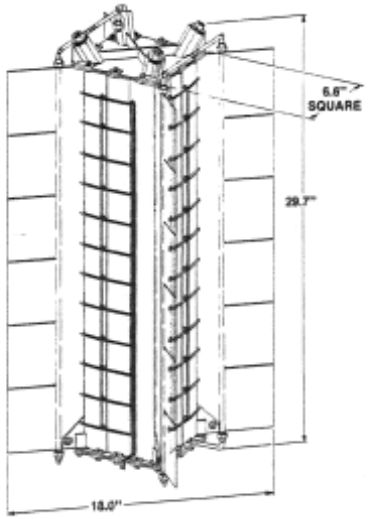


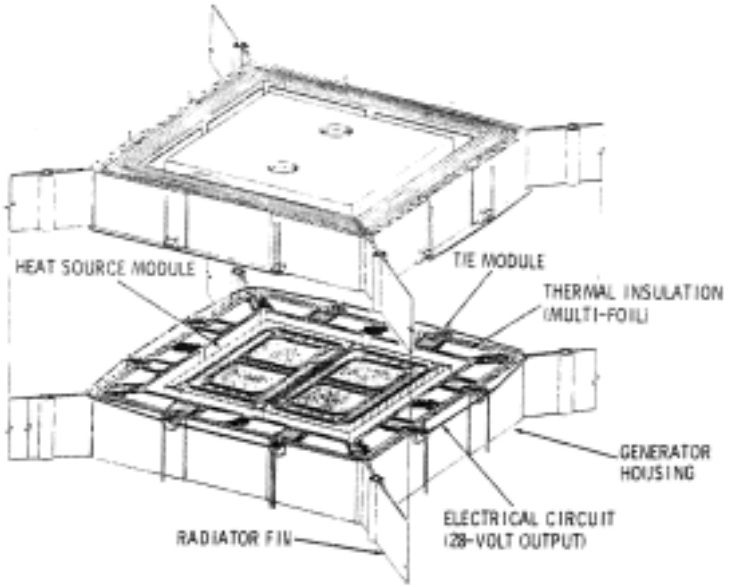
Load-bearing Insulation Skirt

Small RTG Preliminary Concept:

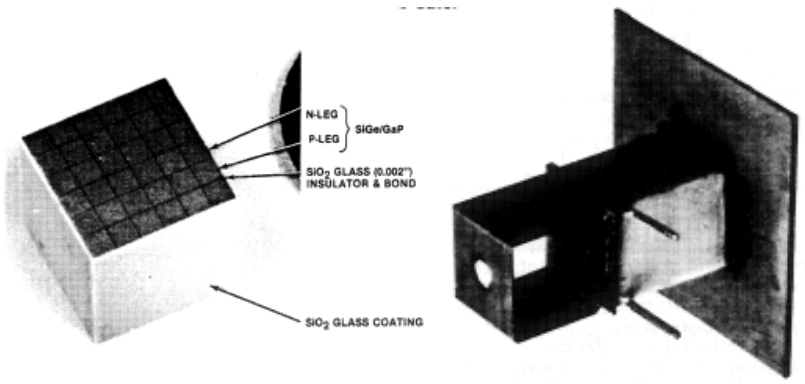
- Power: 20 W
- Weight ~ 7.5 kg
- Efficiency ~ 8% (runs colder than MMRTG)
- Specific power ~ 2.6 W/kg
- Size ~ 25 cm diameter x 20 height
- Flanged interface to transfer heat to spacecraft

Modular Isotopic Thermoelectric Generator (MITG)



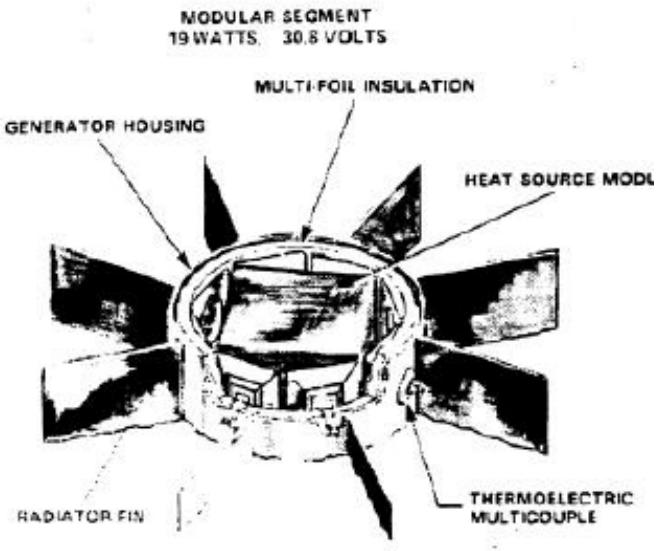


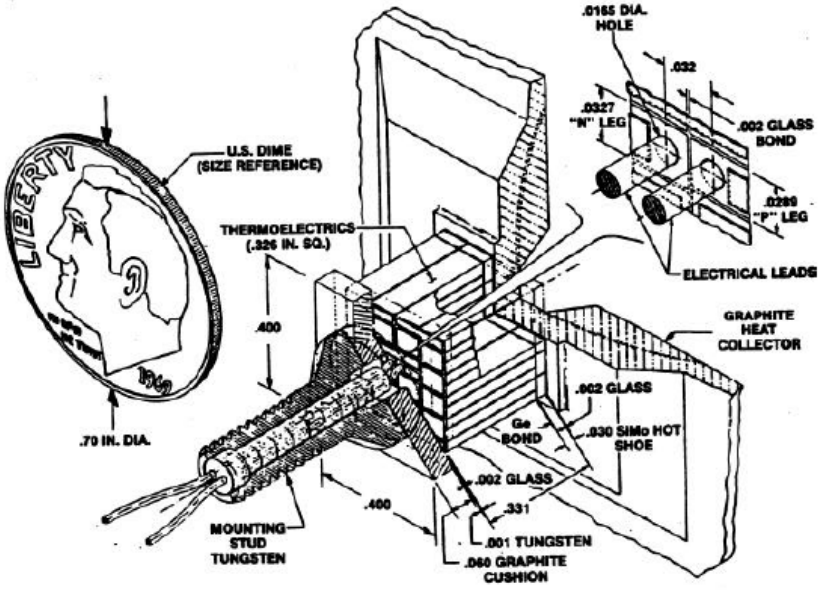
- Work completed in 1983 (device-level)
- Radiative coupling to heat source
- 1 GPHS per square MITG section
- 8 “multicouples” per square MITG section (system “module”)
- Each section delivers 28 V, 16 We (based on GPHS-RTG SiGe performance)
- Can be stacked: performance predictions
  - 12 slices, 192 We ~ 26 kg, ~ 7.1 W/kg



Modular Radioisotope Thermoelectric Generator (Mod-RTG)

- Terminated in 1992 (Ground Demonstration System)
- MITG follow-on system concept
- 1 GPHS, 8 “multicouples” (modules) per round Mod-RTG section
- Each section delivers 30.8 V, 16.5 We (based on GPHS-RTG Si-Ge alloys)
- **Can be stacked: performance predictions**
  - **Full size, 18-section system: ~ 300 We, 6.5% conversion efficiency**
  - **~ 42 kg, ~ 7.0 W/kg (35% gain in specific power over GPHS-RTG)**

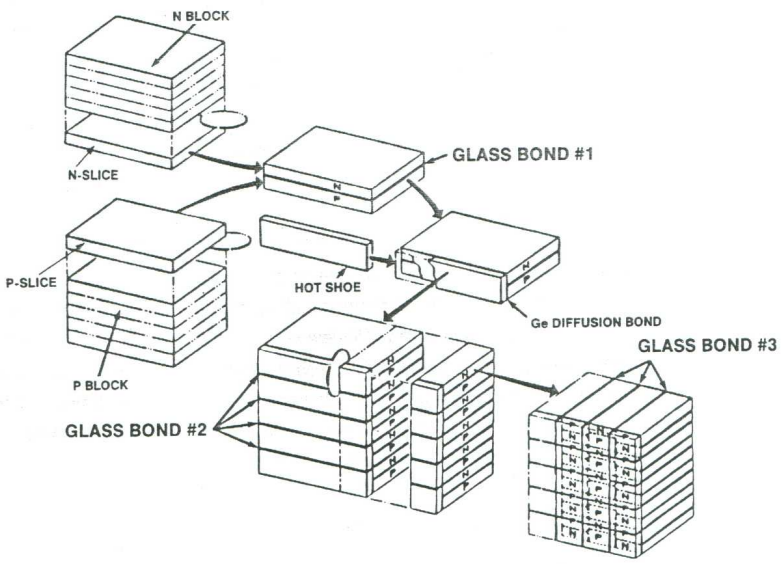


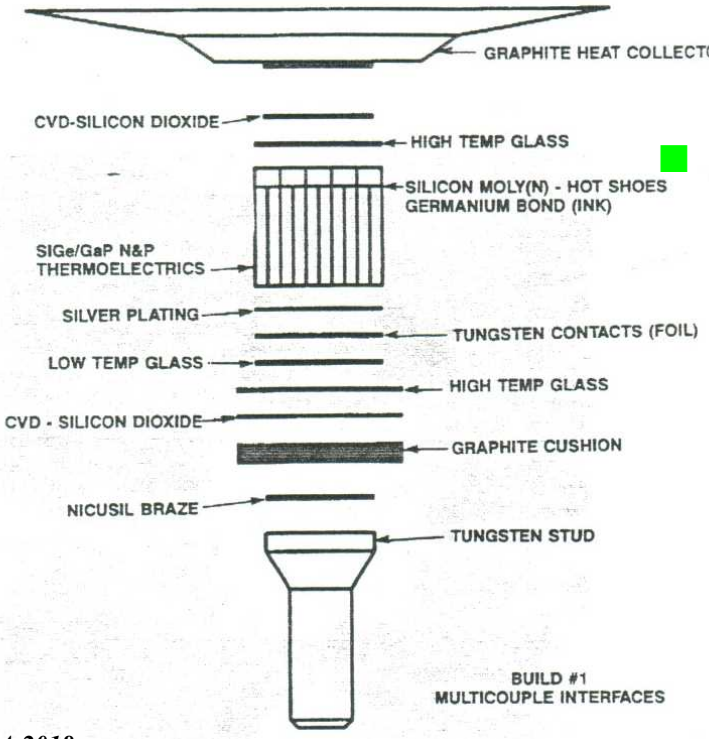


MOD-RTG SiGe Multicouple Technology

MOD-RTG SiGe Multicouple Technology

- 1275K–575K operation
- 8% conversion efficiency at TE device
- Radiatively coupled on hot side
- Specific power projected at 35% better than for GPHS-RTG
- Mostly due to multicouple vs. unicouple





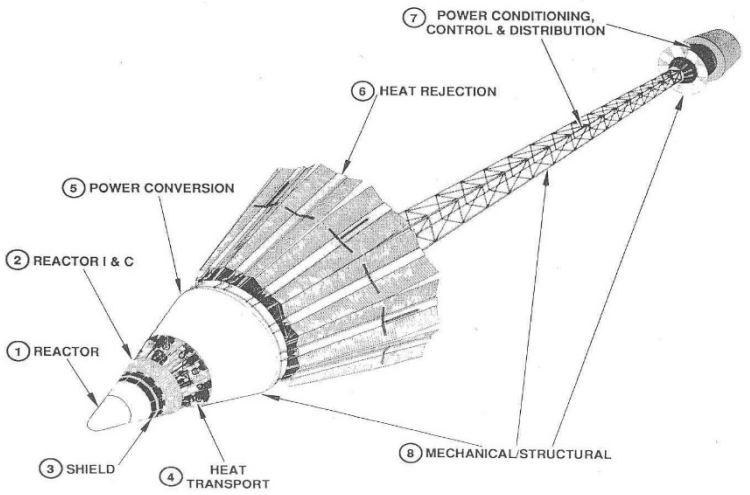
Key achievements

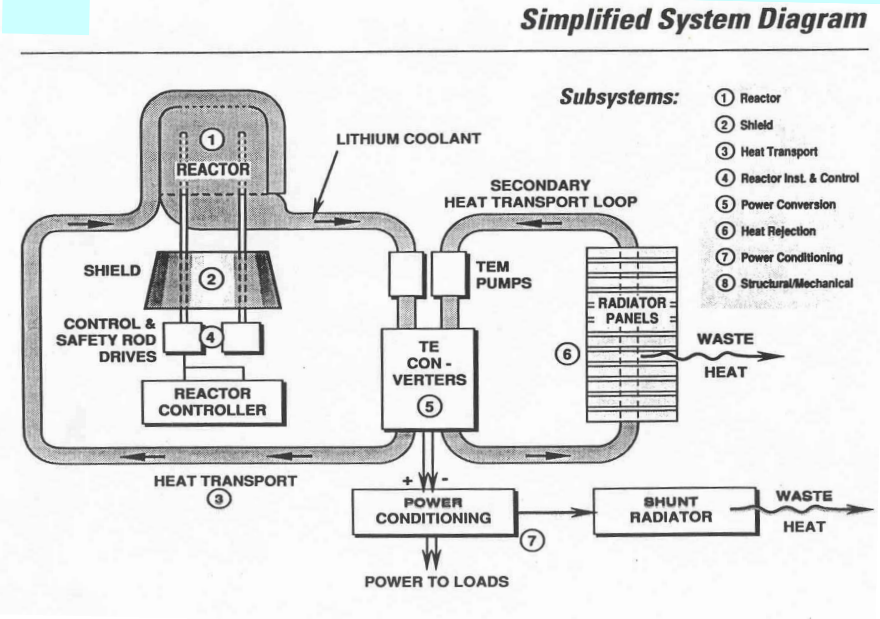
- Achieved TRL ~ 6 in 1992
- Developed reproducible multicouple fabrication and integration processing technology
- Large heat flux concentration using graphite collector
- Developed low alkali glass for bonding legs
- Tested multicouples up to 15,000 hours
- Faster degradation observed (than for unicouples) mainly due to dopant cross-contamination through SiMo hot shoe
  - Problem was corrected in SP-100 effort

High Power Space Reactor Power System (SRPS) SP-100 Concept: SiGe-based Converter Design Characteristics

- 1983 - 1994

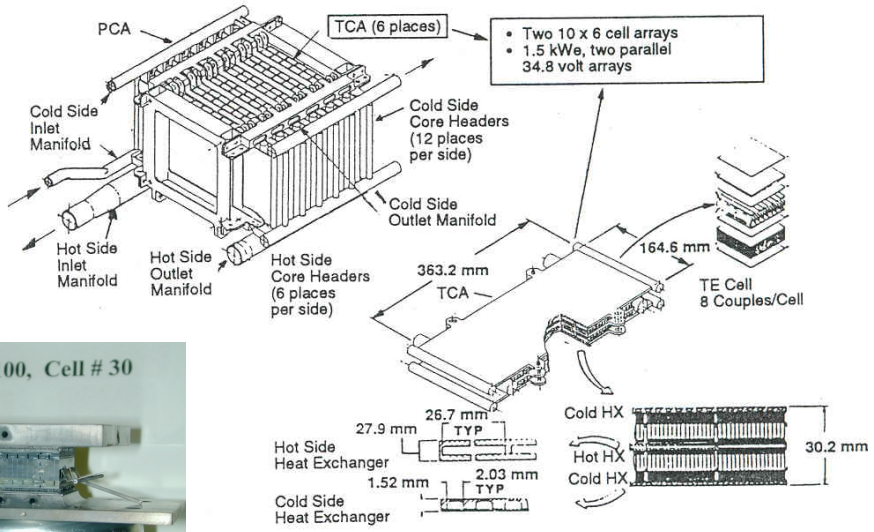
System Performance	SP-100
Electrical Power Output (kW_e)	100
Nuclear Reactor Outlet Temperature (K)	1375
Reactor Thermal Power (kW_t)	2500
Power Converter Operational Temperature range (K)	1275K to 875K
Efficiency (%) Power System Multicouple	 4.0 4.5
Average Radiator Temperature (K)	790
Subsystem Mass (kg)	
Nuclear Reactor	700
Shield	930
Instrumentation and Control for Reactor	320
Primary Heat Transport	520
Power Converter	530
Heat Rejection	960
PMAD	390
Mechanical/Structural	250
Total System Mass	4600

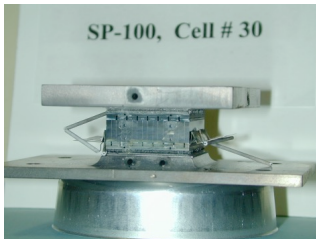




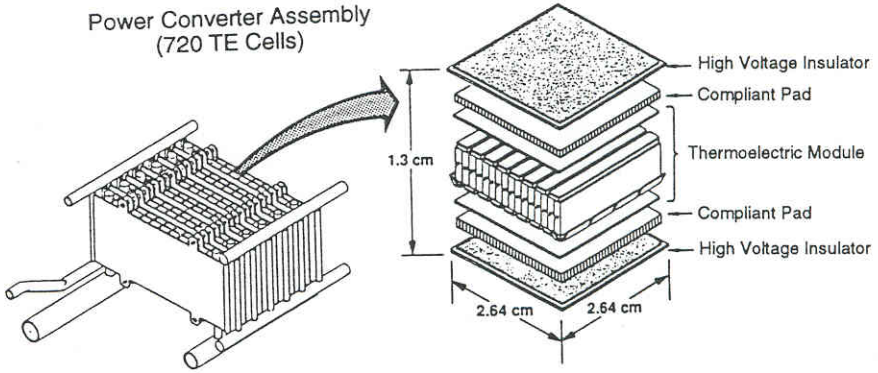
SP-100: Modular 100 kW-Class Thermoelectric Converter Concept

- Power conversion assembly
  - Made of building blocks
    - Thermoelectric cells (multicouples)
    - Thermoelectric converter assembly (6 x10 cell arrays)
  - 8,640 cells required for a 100 kW_e system
  - 5,5 m^2 for a 100 kW_e system
  - Multicouples conductively coupled to hot-side and cold side heat exchangers heated and cooled by Li heat pipes
- Scalability
  - Power levels can be adjusted
  - Concepts from 8 to 200 kW_e have been configured



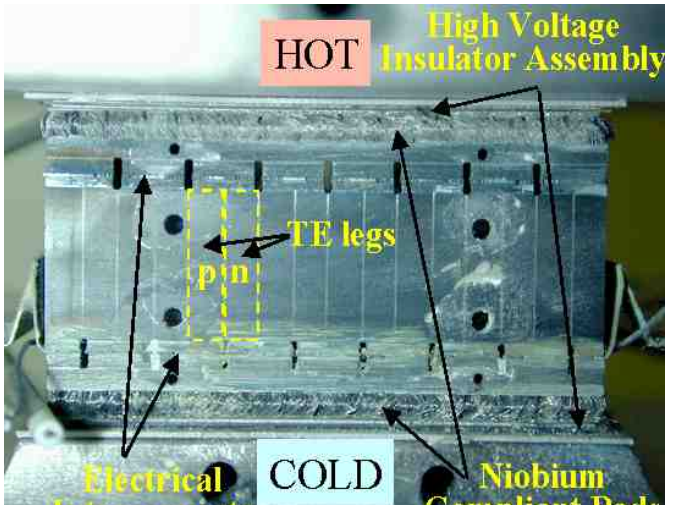


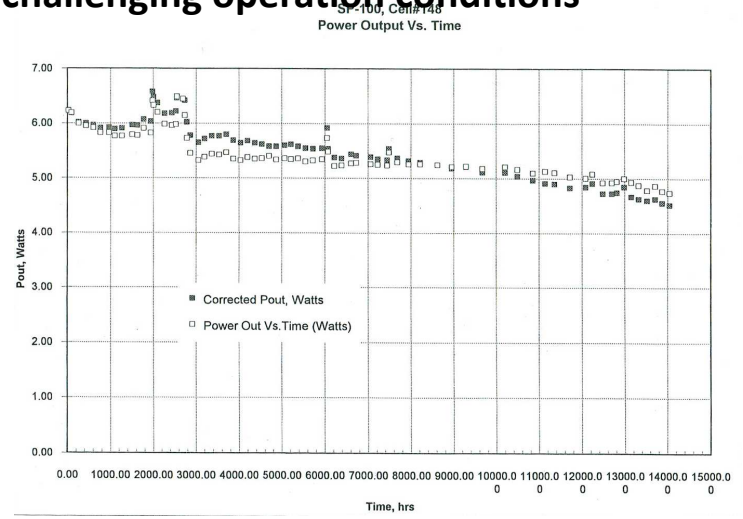
SP-100 Power Converter Components



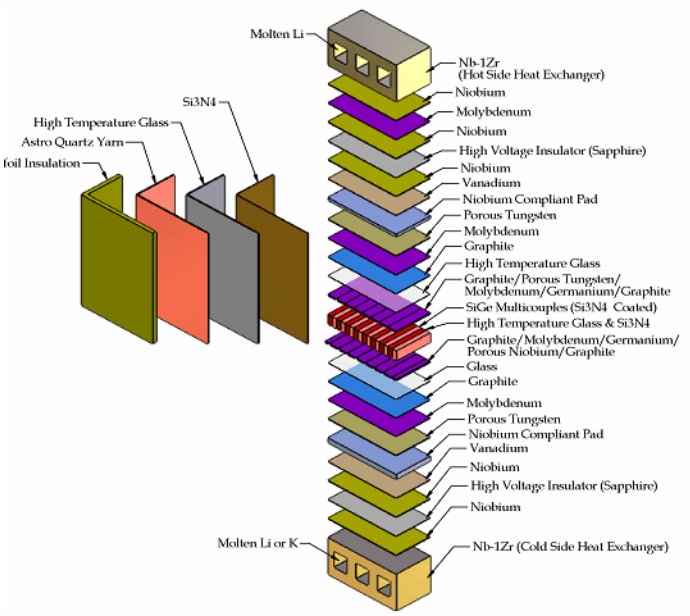
SP-100 SiGe Multicouple Technology

- **SP-100 SiGe Multicouple Technology**
  - 1275K–875K operation
  - 5% conversion efficiency at TE device, 4% at system
  - Conductively coupled on hot and cold side
  - heat flux 5x higher than for RTGs
- **Key achievements**
  - Activities terminated in 1994
  - Resolved faster performance degradation issues (compared with RTGs)
  - Tested multicouples up to 25,000 hours
  - Still some significant manufacturing and performance challenges due to complex technology design and challenging operation conditions





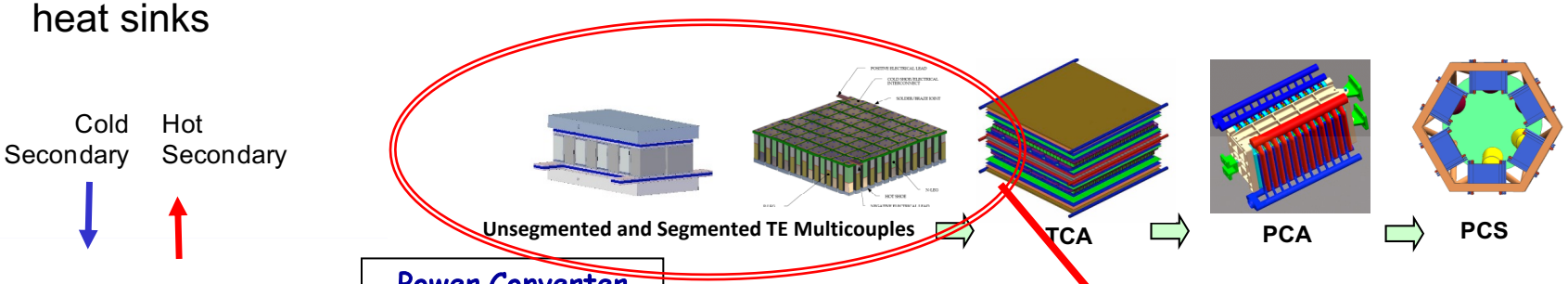
SP-100 Multicouple Stack Details



Advanced TE Systems for High Power Applications

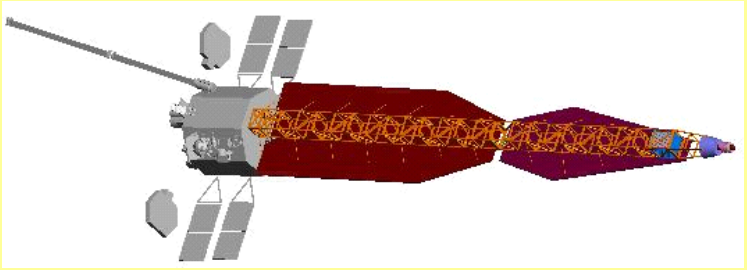
JIMO and Surface Power LM-TE Concepts were based on SP-100 Heritage

- 2003 to 2006 “SP-100 like” technology development was focused on arrays of thermoelectric multicouples grouped into power converter assemblies;
- Used liquid metal heat exchangers to interface with reactor heat source and radiator heat sinks

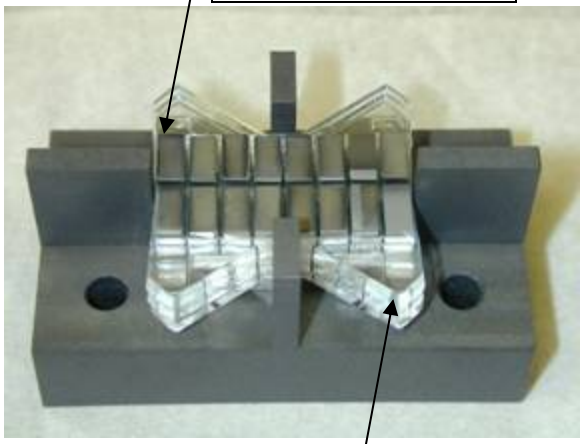


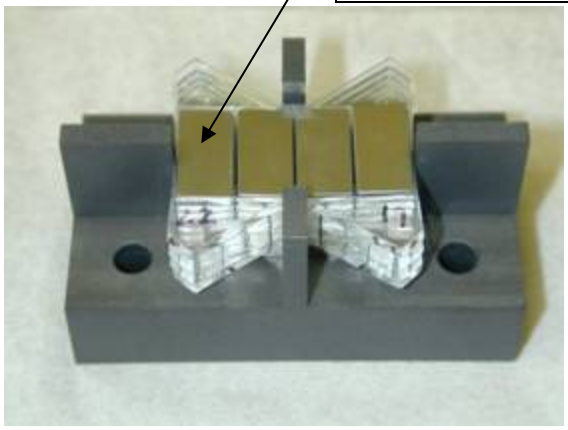
Development of robust high temperature thermoelectric module technology is critical to all applications

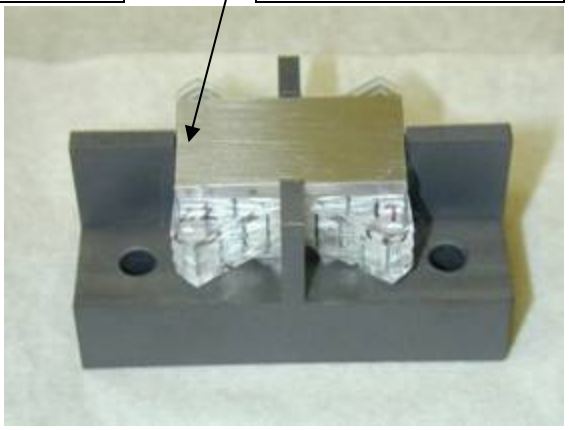
- ***Using practical, scalable fabrication techniques***
- ***Ability to integrate with various heat exchangers***
- ***Ability to reliably survive thermal/mechanical stresses***



2x4 Skutterudite Multicouple for 100 kW SRPS Concept: Proof-of Concept Demonstration

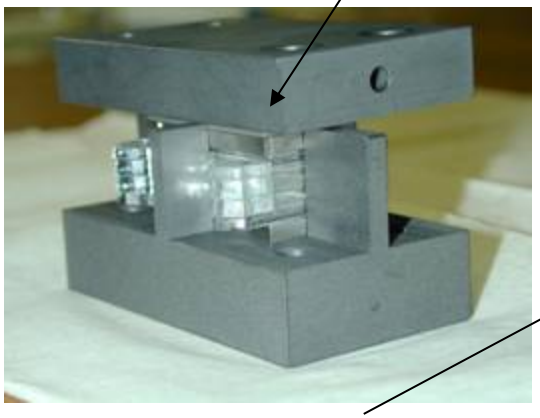


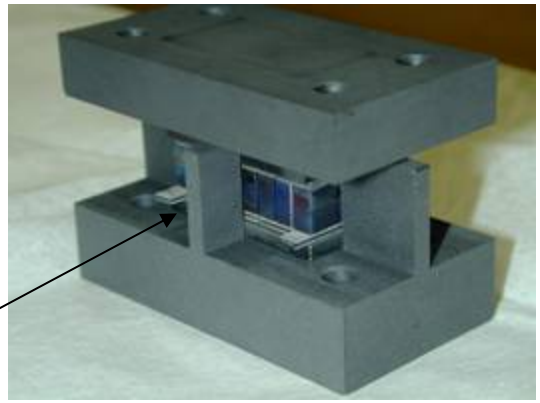




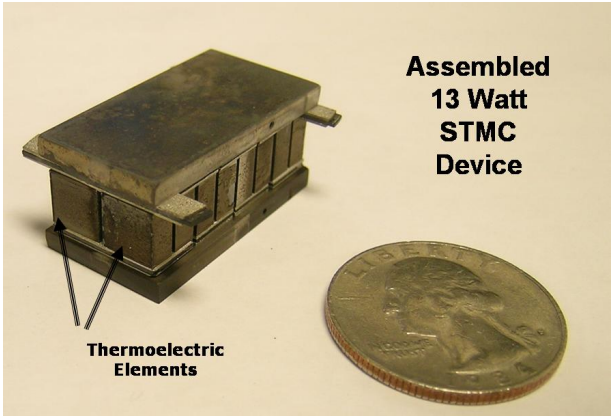
Vaporizable Egg-crates

Die Fixture for 2x4 LT-TMC

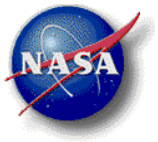




Assembled 2x4 LT-TMC after bonding cycle and egg-crate vaporized



- *Designed for conductive coupling to flat plate heat exchangers*
- *Several proof of principle devices fabricated and tested*



More Efficient Thermoelectric Technologies for Potential Infusion into More Capable Space Power System Concepts

High Efficiency Device Technology Demonstrations

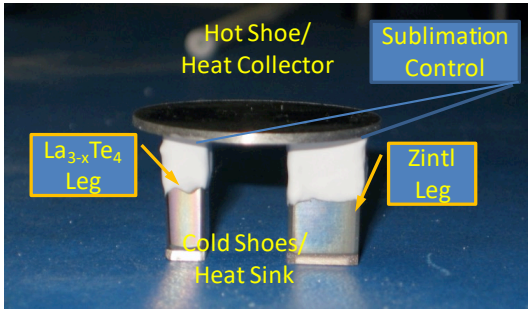
- Developed high temperature couple fabrication and assembly processes
- Couple efficiencies from ~10% (875 K) to ~15% (1275 K)
- 25% to ~ 100% Improvement over Heritage Space Power Systems Couples

Skutterudites (SKD) only `(2006)

Unsegmented "eMMRTG" couple

~ 10%

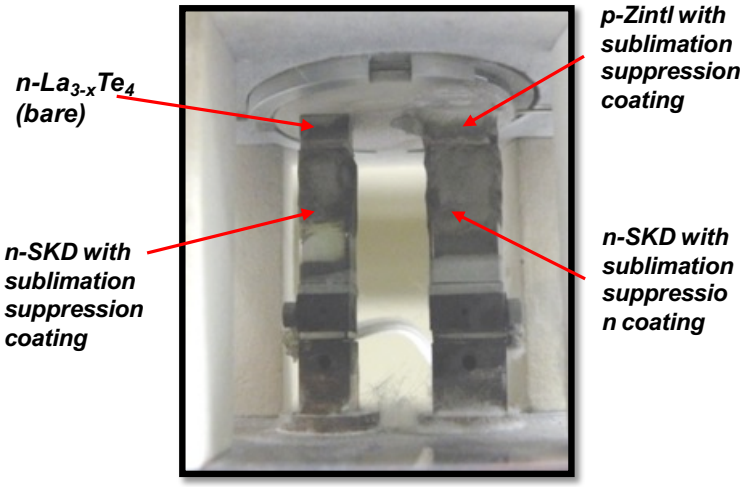
Zintl/$La_{3-x}Te_4$ only `(2010)



Unsegmented "Next Generation RTG" couple

~ 10-12%

SKD/Zintl & SKD/$La_{3-x}Te_4$ (2011)



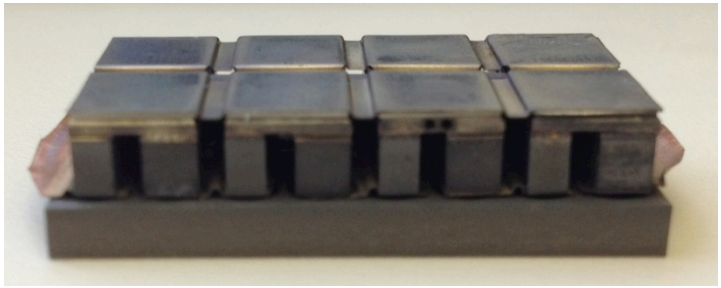
Segmented "Next Generation RTG" Couple

~ 15%

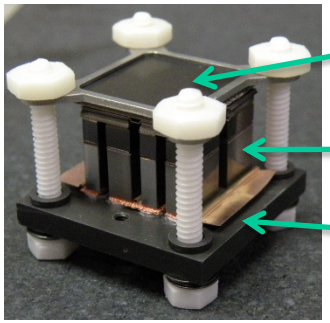
The NASA-funded Thermoelectric Technology Development Project Goal is for > 20% efficient device-level conversion efficiency

Proof-of-Principle TE Multicouple Demonstrations Based on Segmented TE Technology

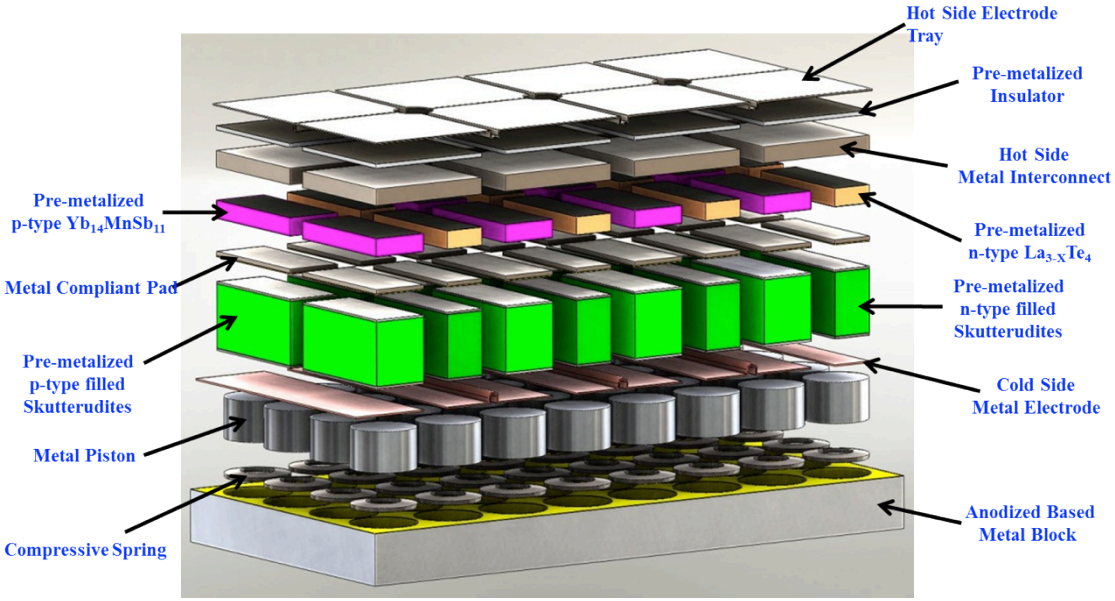
- Based on Segmented TE Couple Technology
  - Includes multiple compliant interfaces to minimize thermally induced mechanical stresses
  - Mechanically compliant designs with aerogel-based thermal insulation
- 1st Generation 4-couple and 8-couple multicouples fabricated & tested (solar furnace, Na HP heat sources)
  - Efficiencies up to ~ 10% measured to date
  - **~15% possible** for 1275/475 K operating temperatures



Skutterudite-only 8-couple Multicouple (JPL)

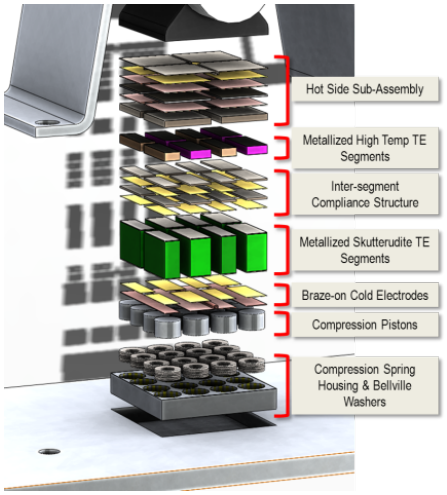


Fully segmented 4-couple TE multicouple for Terrestrial and Space Applications (JPL)



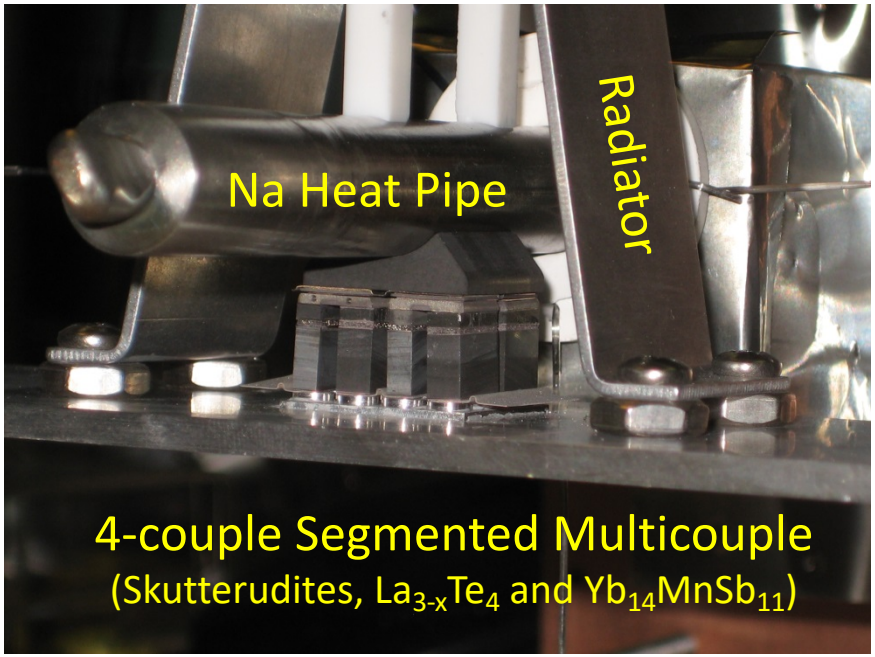
Hermetically sealed Multicouples for terrestrial applications (commercial)

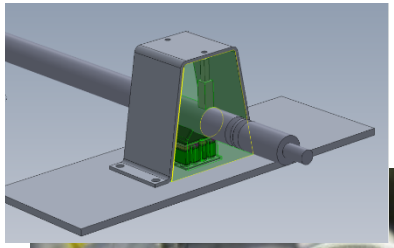
kW-Class Small Fission Power System Concept:
Integration of Heat Pipe, TE Multicouple Converter and Radiator

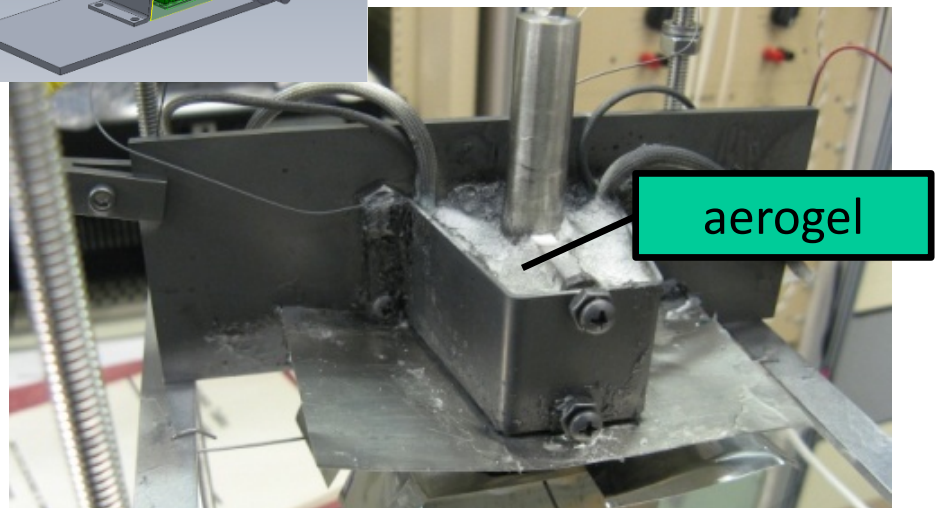


- Pre-installed TE module with graphite saddle onto radiator enclosure
- Slipped assembly onto heat pipe
- Compressively loaded with ceramic posts resting onto heat pipe
- Instrumented, then cast aerogel insulation and sublimation suppressant
- Process could easily be used to populate full length heat pipe in small FPS

Same basic building blocks:
Segmented TE Multicouple, Aerogel thermal insulation



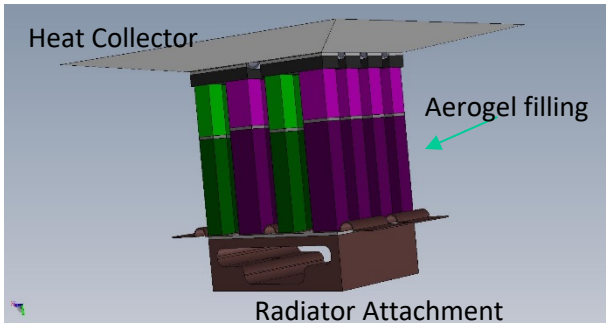


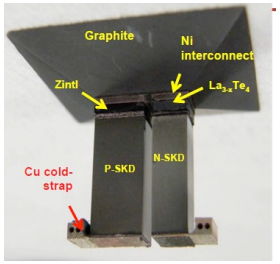


Common Converter Building Block for Space Power Systems: The Segmented TE Multicouple

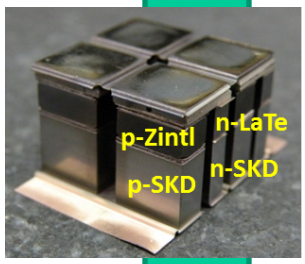
- Common building block is multi-couple segmented TE module
  - Basic multicouple "skeleton structure" can be integrated into cantilevered and spring-loaded module configurations
  - "Skeleton structure" includes:
    - Common "hot shoe" with compliant metal/ceramic header
    - Array of segmented TE couples connected in series/parallel
    - Cold side interconnects

Cantilevered Segmented Multicouple for Modular Next Generation RTG Concept



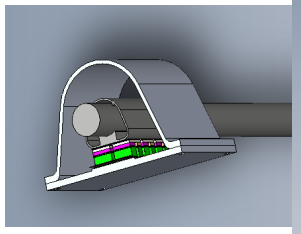


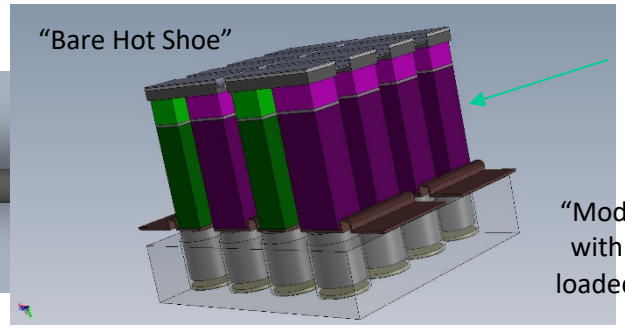
ATEC Segmented Couple



Basic Building Block: ATEC Segmented Multicouple "Skeleton Structure"

- Multicouples could be used for both future RPS and FPS concepts



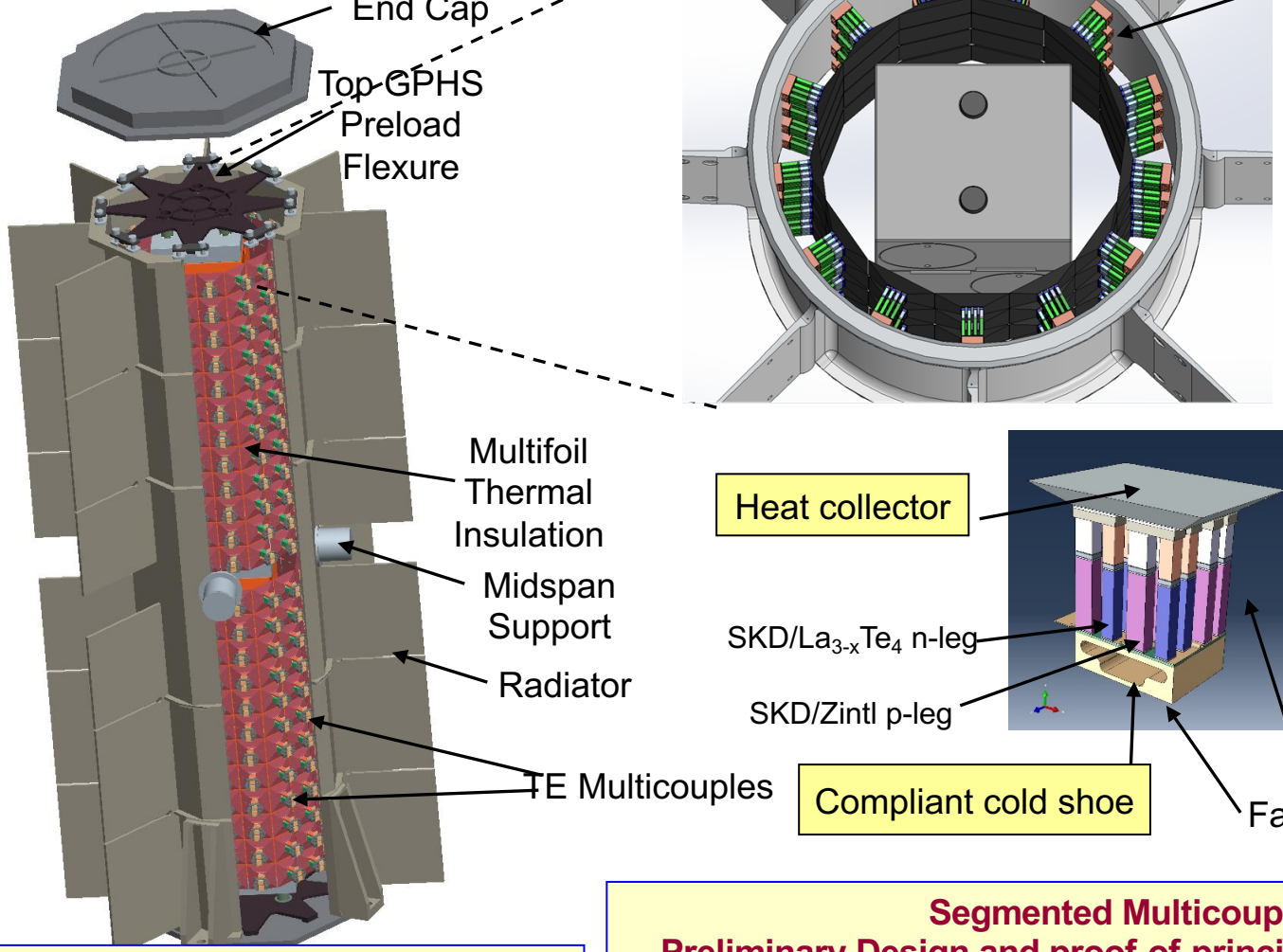


Spring-Loaded Segmented Multicouple for various converter designs

Outline

- Background
- RTGs for Space Mission – Record of extraordinary accomplishments
- Key thermoelectric converter design features in heritage systems and drivers for more capable power systems
- Overview of historical multicouple technologies for advanced system concepts
- Next Generation RTG concept: system modularity as key attribute
- Summary

Segmented Thermoelectric Modular RTG System & Thermoelectric Device Concepts



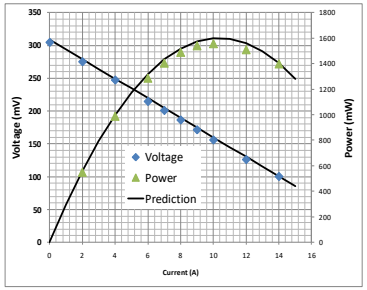
52 TE 8-couple multicouples per 2-GPHS section

Potential Next Generation RTG conceptual design

Segmented Multicouple Preliminary Design and proof-of-principle demonstration

Potential for Modular RTG Capability

~ 2x Conversion Efficiency
over
Heritage Thermoelectrics



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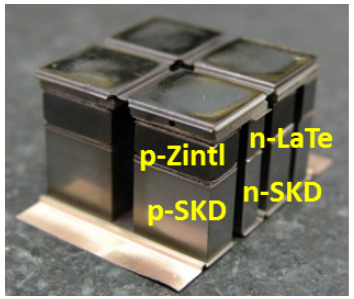

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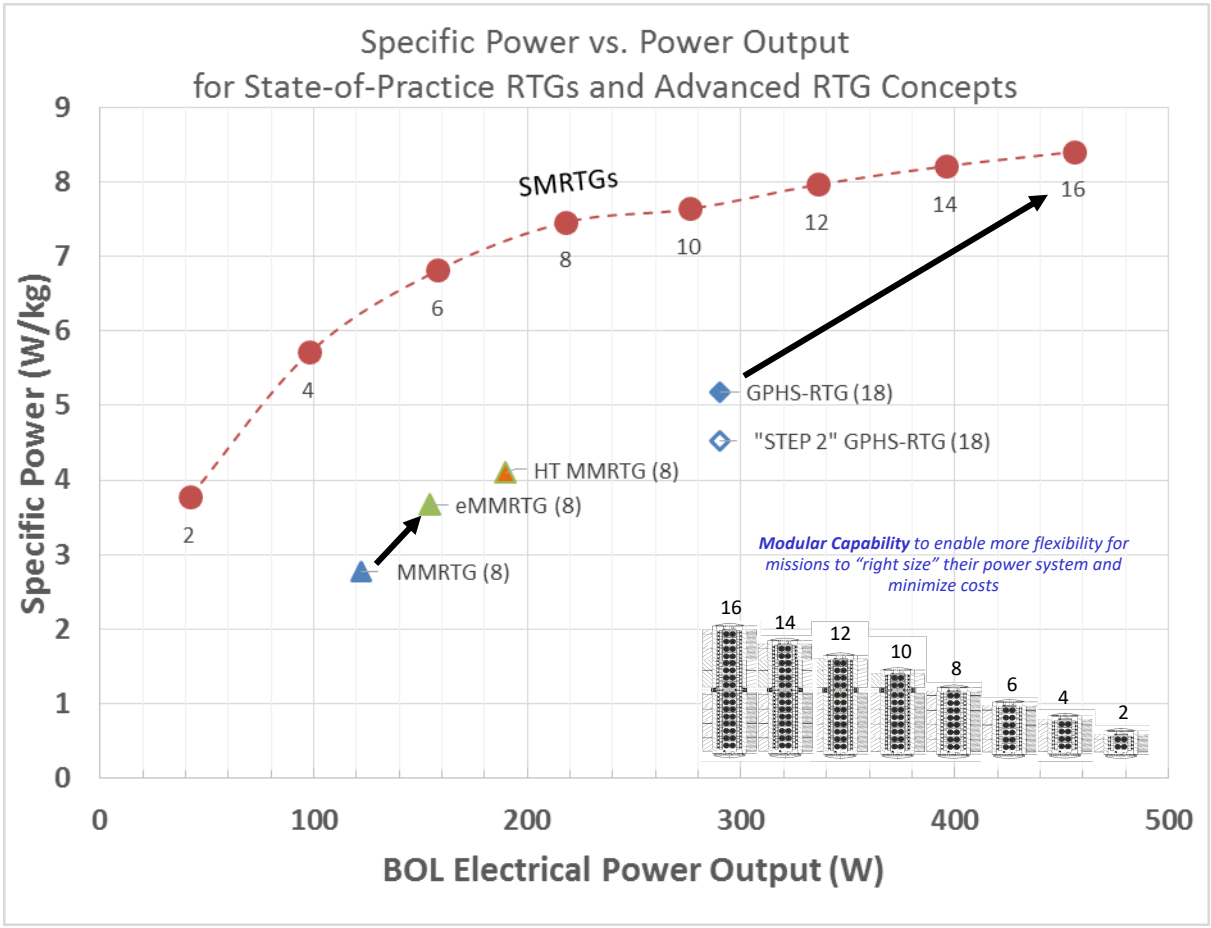
Segmented & Modular
TE Device Technology



More Capable RTG: higher end of design life power, higher specific power and potential for modular system architecture

Based on conceptual design and engineering studies sponsored by NASA, developed by Aerojet Rockedyne and Teledyne Energy Systems, Inc. with DOE guidance (initial study in 2006, updated in 2014)

Outline

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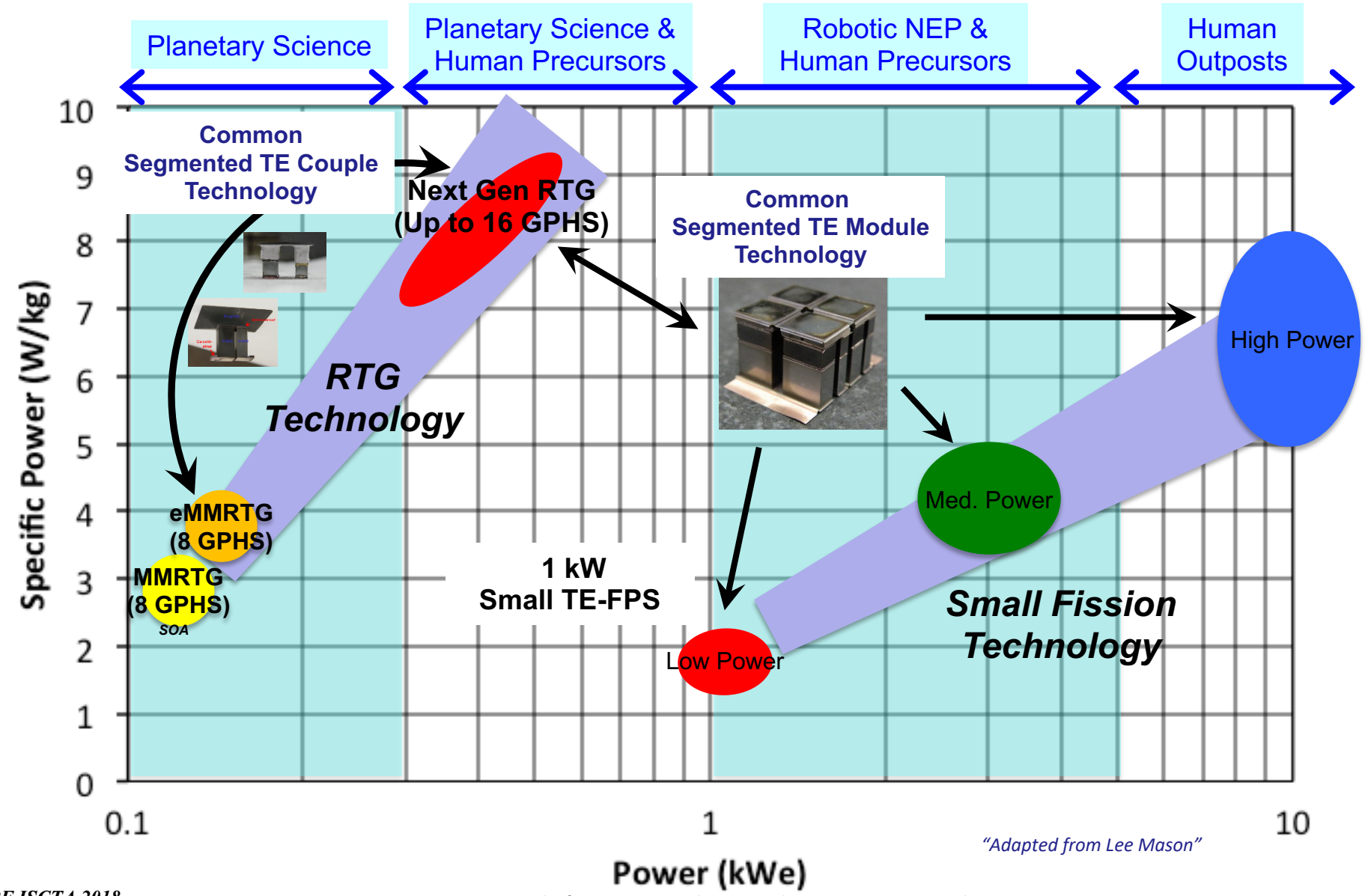
Future Nuclear Power System Concepts: Multicouple Devices as Common Converter Building Blocks



"Adapted from Lee Mason"

Summary

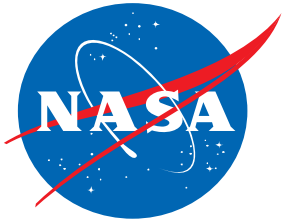
- TE technology has some unique characteristics that make it attractive for a number of applications
- Space systems require absolute reliability and specific power is a key metric
  - Efficiency matters especially in terms of fuel usage
- Modular TE converter architectures and use of advanced manufacturing techniques are highly desirable for both space and terrestrial power systems
  - Effective, robust integration with heat source and radiator for space systems
  - Ability to integrate with heat exchangers at low fill fractions for terrestrial systems
  - All TE converters require the use of effective thermal insulation solutions
- New materials have been infused into > 15% efficient segmented TE modules
  - Potential for applications across multiple platforms up to Th ~ 1275 K
- **Technology currently being developed for potential infusion into modular Next Generation RTG concepts**
  - **400-500W at beginning-of-life, ~ 290 W at end of design life (17 years)**
  - **System modularity based on multicouple technology could enable scaling down to ~ 40 W while maintaining high output voltage requirement**

Acknowlegments

- This work was performed at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration
- The work has been supported by the NASA Science Mission Directorate's Radioisotope Power Systems Program

See

- ***https://solarsystem.nasa.gov/rps/home.cfm***
- ***http://science.nasa.gov/about-us/smd-programs/radioisotope-power-systems/***



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